G

GEIGER AND ELECTRONIC COUNTERS. Twentieth-century physicists first built electronic counters to detect charged particles from radioactivity, then turned them to cosmic ray research, and later combined them in arrays for high-energy particle experiments. In 1908, Hans Geiger built a cylindrical capacitor to help Ernest Rutherford determine the charge on alpha particles. A thin wire with a high voltage ran down the center of a brass cylinder filled with carbon dioxide. A charged particle passing through the chamber would ionize some of the gas in proportion to its charge, setting up a current of ions traveling toward the wall of the tube and electrons toward the center wire; an electrometer needle registered the resultant voltage step. Increasing the voltage on the capacitor increased its sensitivity by creating an avalanche of electrons. The quantity of these secondary electrons depended on the speed and nature of the primary particles. Geiger's initial counter could count up to ten particles per minute and confirmed the double charge of the alpha particle.

Geiger subsequently refined the device by using a sharp needle instead of a coaxial wire for an anode; the additional sensitivity could detect electrons as well as alpha particles, and even photons via secondary electrons knocked out of atoms. But the Geiger counter also registered random, spontaneous counts, even with no nearby radioactive source and especially with maximum sensitivity. In 1928, Walther Müller, a postdoctoral assistant to Geiger at the University of Kiel, designed a still more sensitive counter and found that the spontaneous discharges were caused not by contamination of the gas or metal, but by cosmic rays passing through the chamber. Müller's work turned an apparent defect of the Geiger counter into an advantage, and Geiger counters (or, as they were sometimes called, Geiger-Müller counters) became a prime tool in the fruitful program of cosmic ray physics in the 1930s.

Walther Bothe soon incorporated Geiger counters into coincidence circuits, two counters wired together so as to register a particle when both counters fired together. Bothe and Werner Kolhörster at first measured counts optically, using the electronic output to nudge a mirror and photographic film to record the reflected light. Bruno Rossi, an Italian physicist visiting Bothe's institute, dispensed with the film. A simple logic circuit designed by Rossi ensured that if and only if two counters fired, then a voltage difference on the circuit would result. An experimenter could expand Rossi's circuit to more intricate arrays of counters, firing in coincidence or anticoincidence, with logic gates in the circuit to sort out the particles produced in cosmic ray showers. For example, by measuring the counting rate with and without lead blocks inserted between three Geiger counters, one could determine whether particles originated from the sky or the lead block.

The radar and atomic bomb projects in the United States in World War II developed new amplifiers, pulse-height analyzers, and other electronic devices that would find use in electronic detectors. Rossi worked at Los Alamos on fast timing circuits to measure nuclear processes, such as the time between the emission of prompt and delayed neutrons from nuclear fission. Nuclear energy also provided a market for Geiger counters as radiation detectors. Following the development of vacuum tube amplifiers by the radio industry, Geiger counters were connected to audio speakers to register particle counts as clicks. A popular image of the nuclear age featured the crackle of Geiger counters betraying the presence of nuclear radiation.

After the war, electronic counters became both high art and big science in detectors for high-energy physics. Particle physicists wired new sorts of counters into electronic logic circuits: first scintillation and Cherenkov counters, which converted flashes of light into electronic pulses, and later spark chambers, a sort of flattened Geiger counter with a parallel-plate configuration, and drift chambers and multiwire proportional counters, both of which worked according to the same principle as the Geiger counter. All of these counters generally recorded electronic data instead of the visual output of cloud and bubble chambers, and used high particle counts to provide statistical evidence of phenomena instead of snapshots of individual events. By the 1970s, physicists were using computers to reconstruct particle tracks from complex collections of electronic counters.

Peter J. Westwick

GENETICS is grounded in the papers on inheritance in peas by the Austrian monk Gregor Mendel that he published in 1865. It emerged as a field of biology after Mendel's long-ignored work was rediscovered in 1900 by scientists concerned with what might be learned about the mechanism of evolution from hybridization experiments in plants. In the United States and England, Mendel's laws of biological inheritance were immediately embraced by a number of evolutionary biologists and plant breeders, including William Bateson at Cambridge University, who coined the term "genetics" in 1903. Yet the theory also ran into a good deal of skepticism. The mathematics of Mendelian inheritance seemed to conflict with the one-to-one male-female ratio of sexually reproducing species. Then, too, many characters varied with transmission from one generation to the next and many expressed themselves not as alternates—e.g., tall or short—but in a blended fashion, intermediate between the characters of parents.

However, in 1905, Edmund Beecher Wilson, at Columbia University, and Nettie M. Stevens, at Bryn Mawr, concluded independently that the determination of sex, including the one-to-one sex ratio, was caused in Mendelian fashion by the segregation and reunion of the X and Y chromosomes. In 1909, the Danish biologist Wilhelm Johannsen drew on his studies of heredity in selected lines of plants to propose that variation arises from two sources: one is the influence of

A technician holds a modern version of the Geiger counter, a detector of radiation invented by Hans Wilhelm Geiger (1882–1945) in the 1920s.

environment on the developing organism; the other is slight variation in Mendel's transmitted factors of heredity, which Johannsen called "genes." Johannsen's delineation of these shaping differences gave rise to the concepts of, respectively, "genotype" (the sum of all an organism's genes) and "phenotype" (the characters it displays, which are a product of both its genes and the environment it experiences).

Like Mendel's rediscoverers, Thomas Hunt Morgan, a biologist at Columbia University, came to the study of heredity through concern with the problem of evolution. Initially skeptical of Mendelism, he became a convert to it after 1910, when he observed a heritable mutation—the appearance of a white-eye—in the fruit fly *Drosophila melanogaster,* whose eyes were normally red. Morgan and a team of three graduate students—Calvin Bridges, Hermann Muller, and Alfred Sturtevant—proceeded to scrutinize the offspring of innumerable generations of fruit flies, finding the creatures convenient for the study of heredity because they reproduce very rapidly and in great abundance and because they are cheap to maintain, requiring only jars for housing and rotting bananas for feed.

The Morgan group demonstrated that a number of characters—not only eye color but, for example, wing shape—are transmitted by genes. They also showed that the genes reside on the flies' chromosomes and that occasionally two members of a chromosome pair exchange parts with each other. Called "crossing over," the phenomenon allows characters from genes on the same chromosome to be inherited independently. The Morgan group recognized that the frequency with which such independent inheritance occurs provides a measure of the relative physical closeness—termed "linkage"—of genes to each other. Using frequency data, they were able to draw the first genetic maps—that is, linear pictures of where in linkage units different genes are located along the chromosome. The Morgan group summarized their findings in a highly influential book, *The Mechanism of Mendelian Heredity* (1915). By this time, studies of inheritance in a number of organisms strongly indicated that many traits, including those of an apparent blending nature, are the product of combinations of genes. In 1933, Morgan was awarded the Nobel Prize in physiology or medicine for his pioneering work.

The increasing success of Mendelism, however, was accompanied by debates among biologists about the nature of the gene. Was it a physical entity or some kind of dynamic organizing principle? Convincing evidence that genes are material entities came in 1927, when Hermann Muller, working with fruit flies at the University of Texas, showed that exposing them to X rays would induce genetic mutations. In Berlin in 1935, Max Delbrück, a physicist then turning to genetics, collaborated with two other scientists to try to ferret out information about the actual structure of the gene. Using X rays, they combined experimental data and quantum mechanical theory to account for mutations in terms of the chemical and physical behavior of atoms. Their findings indicated that genes are relatively stable macromolecules susceptible to analysis by physical and chemical methods.

In 1937, at the California Institute of Technology, where he had gone on a fellowship, Delbrück embarked on research with bacteriophage—a virus that infects bacteria and multiplies rapidly inside its host. He saw in this interaction a simple system for the study of genetics, a kind of hydrogen atom for biology. Remaining in the United States because of World War II, Delbrück worked on bacteriophage at Cold Spring Harbor, on Long Island, New York, during the summers with the Italian refugee scientist, Salvador Luria, and Alfred Hershey, a chemist on the faculty of the Washington University Medical School, in St. Louis, Missouri. Their collaboration gave rise to what came to be known as the Phage Group, a small, informal network of viral and bacterial geneticists, and it eventually brought them a Nobel Prize. The Phage Group produced relatively few experimental results of high significance in microbiological genetics, but under Delbrück's guiding influence it focused attention on the problem of self-replication in living organisms, helped recruit a number of physicists into the field, and fostered the use of physical, chemical, and statistical reasoning in microbiology.

In the early 1940s, while the Phage Group was forming, further evidence that genes are some sort of macromolecule engaged in biochemical functions came from the Nobel Prize-winning research of the Americans George Beadle, a geneticist, and Edward Tatum, a biochemist. As the result of previous work in Paris with the biologist Boris Ephrussi, Beadle thought that genes somehow shape the biochemical pathways that produce different eye colors in fruit flies. At each step along the pathway, an assist is given by an enzyme, an organic catalyst essential to the biochemical transformation in which it is involved. At Stanford in 1940, Beadle and Tatum began to pursue the hypothesis with Neurospora, an ordinary bread mold. They triggered genetic mutations in the mold with X rays and analyzed the resulting metabolic variations. They found that, with a specific gene bred into it, the mold could metabolize a given substance, while with the gene bred out, it could not—in short, that the absence of the gene forced the mold into a metabolic error. In 1945, Beadle spelled out the striking import of their research and recent related work by others: "...that to every gene it is possible to assign one primary action and that, conversely, every enzymatically controlled chemical transformation is under the immediate supervision of one gene, and in general only one." That idea was soon distilled into an apothem—the "one gene-one enzyme hypothesis," which became a guiding principle for the emerging field of biochemical genetics.

All the while, many biologists supposed that genes must be proteins, which were known to make up much of the cell and to catalyze its remarkable range of chemical synthesis. The supposition was reinforced by Beadle and Tatum's work, since it associated genes with enzymes, which are proteins. But evidence to the contrary came from a group at the Rockefeller Institute for Medical Research that was headed by Oswald T. Avery. Avery and his associates had worked for a decade to understand why an infectious form of pneumoccous could transform an uninfectious type into a similarly infectious one. In 1944 they reported that the change was caused by a transforming factor in the infectious bacteria that they identified as a deoxyribonucleic acid (DNA).

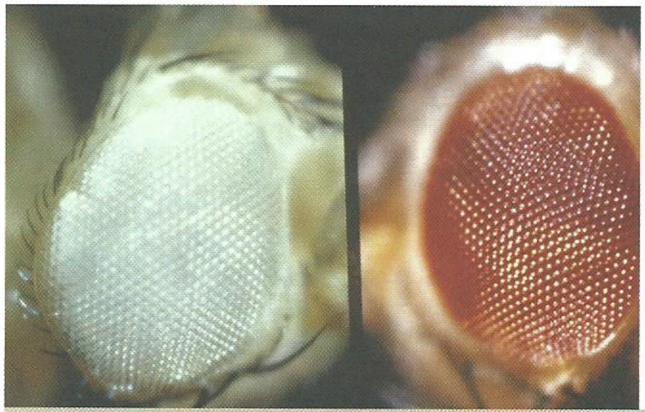
The Avery group's results suggested to some biologists that genetic material might be composed of DNA, but Avery, an older man and a retiring personality, did not push the idea and most biologists remained attached to the belief that genes are proteins. However, members of the Phage Group determined that phage consists of DNA wrapped in a protein coat. In 1952 Hershey, in collaboration with Martha Chase, showed that, when a phage infects a bacterium, it injects its DNA into the bacterial cell, leaving the protein coat on the cell surface. The clear implication of the experiment was that the injected DNA was responsible for the multiplication of the virus inside the cell. At least for members of the Phage Group, the Hershey-Chase experiment strongly argued that the phage's genetic material must be DNA.

In 1951, James D. Watson, a member of the Phage Group, arrived at Cambridge University on a postdoctoral fellowship. Convinced that DNA is the material of genes, he began collaborative work on its structure with Francis Crick, a young physicist attempting a doctorate in biology. Their partnership soon expanded to include Maurice Wilkins, another former physicist who was investigating the physical properties of DNA at Kings College, in London. A key member of his group was Rosalind Franklin, an expert in X-ray diffraction studies of biological molecules. Watson and Crick did no experiments. Rather, they devised tinkertoy models of DNA drawing on chemical and physical data about the molecule, especially some of Franklin's diffraction results with DNA. In 1953, they succeeded in determining that DNA comprises a double helix joined at regular intervals across the distance between them by one of two complementary nucleotide base pairs—adenine with thymine, or cytosine with guanine.

Watson, Crick, and Wilkins held that the structure settled the question that DNA is the genetic material. The structure immediately suggested to them how genes can replicate themselves. The two strands of the double helix would separate, each with its single string of complementary nucleotides; then each would form a template for the creation of a new double helix identical to the first. The physicist George Gamow suggested that the sequence of nucleotides must contain an organism's genetic information in the form of a code. By 1964, biologists had demonstrated experimentally that specific sequences of three base pairs code for specific amino acids. Through a complicated biochemical mechanism, a series of such triplets is translated at a cellular site into a chain of amino acids, which enfold themselves into a specific protein—for example, a constituent of the eye—involved in the organism's structure or, as in the case of an enzyme, figuring in one of its processes, like metabolism.

The working out of the genetic code enabled biologists to begin studying gene function at the molecular level. Their task was greatly facilitated by several experimental and technological innovations, including in the 1970s the technique of recombinant DNA, which allowed the removal of single genes from one organism and their insertion into another; in the 1980s, table-top machines that would determine the sequence of base pairs in a strand of DNA; and, in the 1990s, the creation of computerized databases that made available on the World Wide Web the DNA sequences in the genomes of human beings of laboratory organisms such as yeast and mice. A century after the rediscovery of Mendel's papers, genetics was a highly populated, multi-disciplinary field, wealthy in resources, and rich in promise for understanding inheritance, development, and disease.

DANIEL J. KEVLES



The white mutation (left) of the normal or wild fruit-fly eye (right)

GEOGRAPHY has its roots in ancient efforts to describe the surface of the earth, the form and extent of its lands and seas, and all that is observed in them. The peculiarly modern, European art of geography, as it emerged in the Renaissance, combined mathematical delineation and historical description with varying emphases. For Renaissance scholars, geography was both a body of knowledge recovered from the classical past and a newly discovered art of systematically ordering knowledge of the earth. The transmission of the *Geographia* of Claudius Ptolemy (c. 90–168) from Constantinople to Italy and its translation into Latin early in the fifteenth century was central to making the mathematical description of the earth's lands and seas the core of the new art of geography. It gave instructions for arranging geographical knowledge according to a coordinate system of parallels (latitudes) and meridians (longitudes) and for projecting those lines onto flat surfaces. Renaissance geography was closely tied to the production of maps of the earth's surface and its separate divisions, culminating in the first "atlases" of the Low-country cartographers Gerhard Mercator and Abraham Ortelius in the mid-sixteenth century.

This Renaissance "invention" of geography was sponsored by centralizing states making ever more universal claims to legitimacy. By advertising the usefulness of their art for administering and defending principalities and cities, geographers secured more or less official roles in European states from the sixteenth century. As these states began to explore and trade overseas, geographers used words and pictures to help interpret, manage, and celebrate novel discoveries and new possessions for kings, princes, and churches. Geography also carried all the prestige of humanism and the mathematical arts. Sebastian Münster, author of the *Cosmographica universalis* (Basel, 1544), was typical in advertising geography as the essential study of the active Christian prince. How could anyone understand Homer and Virgil, the campaigns of Caesar and Cato, the acts of God, the wanderings of the Jews, and the missions of the Apostles, without geography?

The Protestant Reformation gave added impetus to official patronage. As reformed and counterreformed princes and cities turned to the foundation of gymnasia and universities, geographical systems assumed a pedagogical and doctrinal function, exhibiting God's wise design of the world. The mathematical basis of geography was progressively refined as a theater for God's providence in the *Systema geographicum* (Hanover, 1611) of the theologian Bartholomäus Keckermann and the *Geographia generalis* (Amsterdam, 1650) of the Dutch physician Bernhard Varenius. Varenius's book was one of the most influential geographical systems of the seventeenth and eighteenth centuries. Isaac Newton edited the second and third editions despite Varenius's Cartesian leanings. In the work of the Jesuit Athanasius Kircher or the globe-maker Vincenzo Coronelli, who served Louis XIV at Versailles, mathematical techniques imbued geography with a renewed sense of cosmographical mission under the sponsorship of Roman Catholic Counter-Reformation and royal absolutism.

In the eighteenth century, geography flourished as a descriptive science with a mathematical foundation, often with an appeal to divine design. Enlightenment geography aligned itself programmatically, with the "systematic spirit" and against the "spirit of system," often restricting itself to positive description and tying itself ever more firmly to a technical symbolic language. Although it relied upon the observations of travelers and field surveyors, geography was essentially a product of the cabinet. While maintaining its focus on devising critical and systematic descriptions of the earth's surface, geography expressed its cosmographical ambitions increasingly by attempts to standardize and universalize the language of geographical description—to establish uniform topographical languages and cartographic symbolism (including map scale).

These efforts reached their zenith in Enlightenment France with Cassini's trigonometric charts of France, the collection of maps for military purposes at the Dépôt de la Guerre (founded 1688), and the closely associated cabinet of J. B. B. d'Anville. Here, geography began to converge with and restrict itself to cartographical description, while occupying the center of a web of skills including the work of field surveyors, instrument makers, and engravers. Geographers such as d'Anville distinguished themselves from lesser workers by their ability to sift and compile geographical information critically and express it in ever more precise and standardized languages, especially its graphic and mathematical expression on a chart. In practice, however, the lines between positive description and philosophical speculation were ill defined. Geographers such as Philippe Buache and Nicolas Desmarest entered into debates over the nature of continents, seas, earthquakes, volcanoes, river basins, and mountain ranges—topics often labeled "physical geography" and "theory of the earth" to distinguish them from "geography" proper.

In Protestant Europe, where geography remained tied to natural philosophy and natural theology, geographers discussed such topics as the causes of the tides, the heat of the tropics, seasonal rains, the decrease of temperature with elevation, and so on. Political geography, human geography, mineral geography, plant geography, and zoogeography emerged as distinct fields, justified principally through their service to natural theology. All exposed the wise hand of Providence by revealing the diversity and distribution of created things, and the balances and economies of nature (language eschewed by French geographers). In Germany and Scotland, at Hamburg, Edinburgh, and Göttingen, in works such as A. F. Büsching's *Neue Erdbeschreibung* (11 vols., 1754–1792) and Christoph Ebeling's *Erdbeschreibung und Geschichte von Amerika* (7 vols., 1793–1816), geography took the form of theologically informed gazetteering aimed at developing industrious, purposeful citizens of the world such as great merchants and administrative officials. At Göttingen, under the auspices of Gottfried Achenwall and A. L. Schlözer, geography was closely allied with statistics and political history *(Staatenkunde)*. Immanuel Kant, who spent most of his forty years at Königsberg lecturing on "physical geography" (including physical anthropology), promoted geography's "extensive utility," supplying "the purposeful arrangement of our knowledge, our own enjoyment, and plentiful material for sociable conversation." Johann Reinhold Forster and his son Georg Forster, who together accompanied James Cook on his second expedition around the world from 1772 to 1776, similarly used geographical exploration to demonstrate the providential design of the world and to make its audience into active witnesses and instruments of providence. In his German translations of contemporary voyages and in his briefer, essayistic works, the nomadic younger Forster decisively focused geography on active exploration and the gradual emergence of underlying dynamic laws and processes.

Toward the end of the eighteenth century, the natural-historical concern with systematic collection, classification, and exposition gave way to philosophical concern with *dynamic* processes and physical causes. Taking inspiration from the Forsters' "philanthropic" approach to understanding the reciprocal influences of nature and human civilization, the Prussian mining official and naturalist Alexander von Humboldt sought physical and historical laws in systematic geographical investigations of everything from climate to language and art. Humboldt shunned the term "geography" and referred to his science as "physics of the earth." As the most renowned traveler and naturalist of the early nineteenth century, Humboldt put the systematic spatial analysis of phenomena usually left to physicists and natural historians—rocks, terrestrial magnetism, atmospheric temperature and chemistry, plant and animal species, anything open to calibrated and standardized perception—at the center of geography. He also emphasized the aesthetic and emotional responses of the traveler. And he stressed that records of medieval travel and conquest, including the works of Christopher Columbus, be preserved and rehabilitated as important geographical sources. Although Humboldt omitted God from his unfinished *Kosmos* (1845–1862, subtitled "sketch of a physical description of the world"), his dual revelation of the lawfulness of nature and the progress and limits of human knowledge of nature was implicitly congenial to a recognition of divine design.

Humboldt's contemporary Carl Ritter presented geography as a comparative study of the world's "terrestrial units" that supplied the key to a developmental understanding of the history of civilization, expressly overseen by divine providence. As delivered for three decades at the newly founded Berlin University and at the Berlin Military Academy and in his massive but unfinished *Erdkunde* (1817), Ritter's demonstration that civilization had migrated from East to West influenced generations of statesmen, soldiers, and scholars. Among them was Arnold Guyot, whose Protestant geographical theodicy found a home at Princeton University after 1848. In Britain, Mary Somerville discovered a similar providence at work in geography: both objectively, in the interaction of physical forces over the surface of the globe to produce geographical laws *(Physical Geography,* 1848), and subjectively, in the progressive interaction of the different branches of the physical sciences in geographical science *(On the Connexion of the Physical Sciences,* 1834).

Geographical societies began emerging in the late eighteenth century, imbued with a civilizing mission and informed by this sense of divine lawfulness The Association for Promoting the Discovery of the Interior Parts of Africa, founded in London in 1788, was followed by groups in Paris (1821), Berlin (1828), London (1830), Saint Petersburg (1845), and New York (1851). These metropolitan societies brought together army and navy officials, statesmen, and scholars to promote exploration and publish maps and accounts of voyages. Although membership waned in mid-century, it revived in the 1860s and 1870s with the recognition of the centrality of geography to imperial expansion and the cultivation of national identities. Between 1870 and 1890, the number of geographical societies in Europe quadrupled to over eighty, driven by the establishment of provincial geographical societies. In 1875, these societies began convening quadrennial International Congresses of the Geographical Sciences. They also encouraged the proliferation of popular geographical magazines and literature. Taking their cue from Germany, where geography was established in natural science faculties, and where academic geography and geographical societies had close ties, geographical societies urged that geography be taught in universities and secondary schools. In 1871, after the Prussian victory over France, the Paris society and the ministry of education established a Committee on the Teaching of Geography and a number of professorships at French universities. In the 1880s, the Royal Geographical Society of London succeeded in establishing chairs of geography at Oxford and Cambridge.

In the universities, geography was dominated by the prevalent enthusiasm for evolutionary theories. Friedrich Ratzel, who trained with Ernst Haeckel in Jena before settling at Munich, Halford Mackinder at Oxford, Alfred Hettner at Tübingen, and William Morris Davis at Harvard all argued that the geographical diversity of humans resulted from the variation of physical conditions over time and space. The Russian exile Peter Kropotkin and the Scottish social critic Patrick Geddes stressed the independent laws of organisms in interpreting responses to inorganic conditions. Paul Vidal de la Blache and Otto Schlüter insisted that human modes of social life (lifestyles, *Kulturformen, genres de vie)* shaped the landscape.

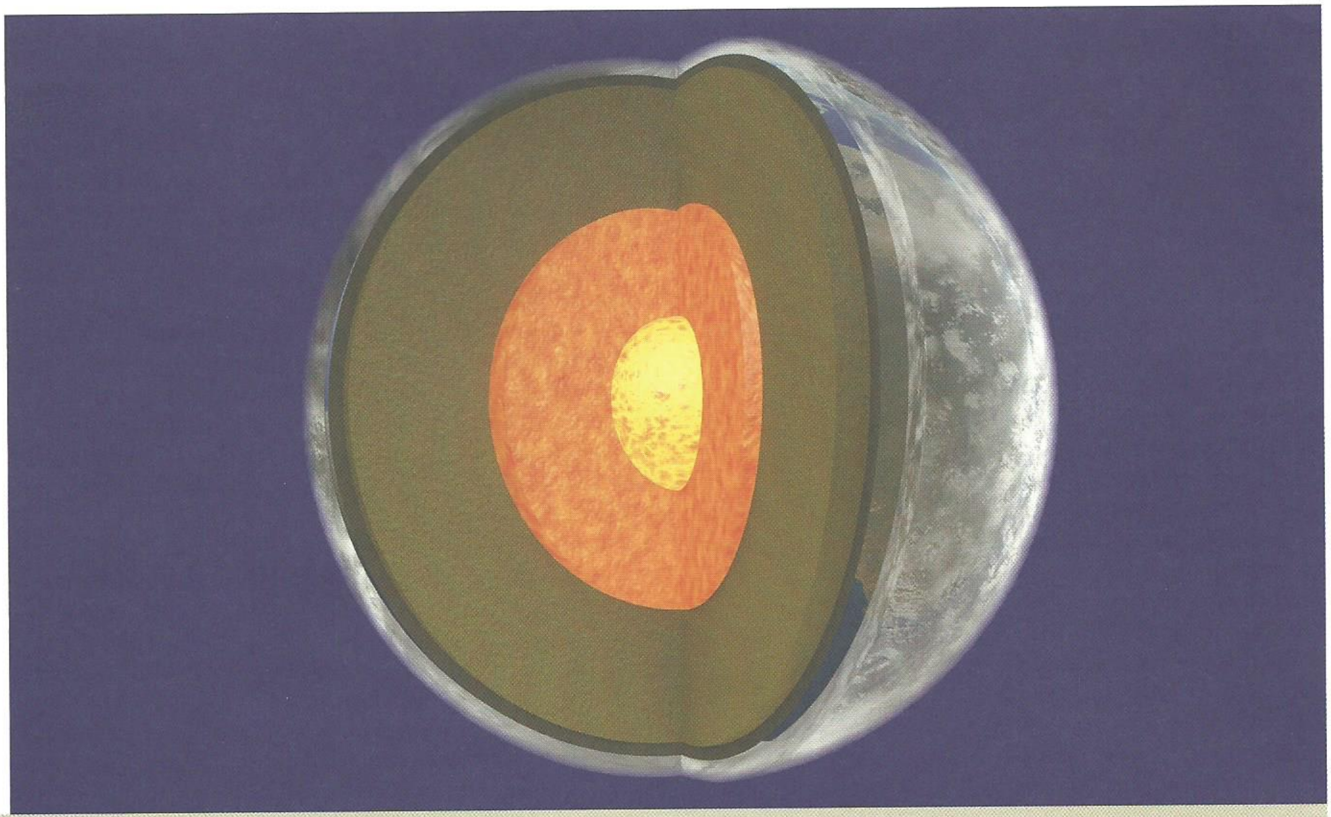
Regardless of their understanding of evolution, academic geographers took the region or the landscape as the fundamental unit of analysis. A few modern geographers explicitly abjured questions of evolution, and claimed that the task of the geographer was to comprehend the unique character of regions or landscapes, without attributing causality to any particular factor. For all their sometimes bitter disagreement, Carl Sauer at Berkeley and Richard Hartshorne at the University of Wisconsin agreed that regional description lay at the heart of scientific geography.

Between the 1950s and the 1970s, geographers enthusiastic about the so-called "quantitative revolution" rejected Hartshorne's strictures, and argued that by using quantification and statistics, geographers could discern the laws of social dynamics. More recently, geographers have analyzed the subjective experience of space and produced "behavioral geographies" and "mental maps."

The very ubiquity of geographical knowledge made it difficult to define the field. Since geography became an academic discipline in the late nineteenth century, its diffuseness has fueled a great deal of historical writing by academic geographers concerned with defining and defending the scientific territory and prestige of their field. This literature, rife with talk of "disciplinary crisis," is understandably preoccupied with discovering the essence of geography in past founders and precursors. Hartshorne's *The Nature of Geography* (1939) drew up a historical lineage and philosophical foundation for the discipline that established geography as a descriptive science of regional differentiation. It remains an influential interpretation of the history and philosophy of geography. Other geographers have adopted philosophies from phenomenology and logical positivism to Marxism, structuralism, and postmodernism in the search for philosophical foundations. In the 1990s, the emphasis began to shift to studying the institutional, political, and social contexts, interests, and languages of earlier geographers. The bread and butter of geography, though, has remained the training of school teachers and the preparation of regional descriptions applicable to a variety of policy needs.

Micharl Dettelbach

GEOLOGY. The word geology as a general term for the study of the earth was popularized in the late eighteenth century by the Swiss naturalists Jean André De Luc, who



In this computer model of the earth, the core (molten iron and nickel) appears in yellow; the outer core (also molten), the seat of magnetism, in orange; the mantle (viscous), on which the crust swims, in brown.

made his career in England, and Horace Bénédict de Saussure, famous for his voyages in the Alps. Abraham Gottlob Werner disliked the term as being too suggestive of theorizing, and promoted the alternative "geognosy." But when a group of Englishmen decided in 1807 to found a society for the study of the earth that eschewed the practical, utilitarian goals of the Continental mining schools, they called it the Geological Society of London. Within two or three decades, geology had its own specialists, societies, textbooks, and journals, the Geological Society's Transactions being the first. Worldwide, the word geology (or its cognates) rapidly became the preferred term for the study of the earth.

Geologists generally divided their specialty into two parts: historical geology, which reconstructed earth history using stratigraphy and paleontology, and physical geology, which investigated the earth's structure and causal processes. The latter consisted of mineralogy, diminished from the overarching category for the study of the earth to a mere subdiscipline, petrology, and structural geology.

The successes of historical geology were manifest in the outlines of the stratigraphic column as worked out by the mid-nineteenth century. Field work with a hammer and a map was the preferred way of investigating, and the geological map an ingenious way of summarizing the results. Georges Cuvier and Alexandre Brongniart produced a pioneering map of the Paris area in 1812. The first national geological map, of England, was prepared by William Smith in 1815; the Geological Society's map followed in 1819. Although these maps were expensive and time-consuming to produce, state governments set up geological surveys to prepare them because of their economic importance for the extractive industries and agriculture. The French began fieldwork for a national geological map in 1825. The British Geological Survey was founded in 1835, followed by the Canadian (1842), the Irish (1845), and the Indian (1854). In Europe, the Austro-Hungarian Empire and Spain created surveys in 1849, Sweden and Norway in 1858, Switzerland in 1859, Prussia and Italy in 1873, and Russia in 1882. The American states founded their surveys early: Massachusetts and Tennessee in 1831 and Maryland in 1833, but a national survey was not created until 1879.

Though the work of mineralogists and petrologists attracted less public attention than that of the historical geologists, their field rapidly moved ahead in the nineteenth century. And although they too carried out field studies, they retained their ties to chemistry and the laboratory.

Historical and physical geology supposedly worked in concert, but the results obtained in the one frequently held little interest for the other. Nonetheless, geologists sought ways of presenting a coherent picture of the earth. One possible strategy, tried by Charles Lyell in his *Principles of Geology* (1830–1833), made the study of present geological processes a necessary key to understanding earth history. Although rejected by most geologists, it provoked a useful methodological discussion.

A second strategy looked for an overarching causal process that could elucidate the details of the stratigraphic record. For most nineteenth-century geologists, the preferred hypothesis was that the earth had cooled and contracted. The nebular hypothesis proposed by Pierre Simon de Laplace and William Herschel, and the work on rates of cooling by Jean Baptiste Fourier, supported their model. In 1831, the French geologist Élie de Beaumont suggested that as the earth had cooled from a molten body, the crust at intervals had buckled under the strain, throwing up mountain chains and exterminating whole genera in the great floods that coursed down their sides. Variants of this theory, and criticisms of it, flourished for the rest of the century and culminated in the four-volume *Face of the Earth* (1883–1904) by Eduard Suess, Professor of Geology at the University of Vienna. According to Suess, the molten center of the earth had once been covered with a thin, solid crust. As the earth cooled, portions of the crust collapsed, creating ocean basins. Later, the remaining higher areas became unstable, and collapsed in turn, forming new ocean basins and leaving former ocean beds exposed as new continents.

It was a triumphant moment for geology. Two great geologists summed up the history of their science during the nineteenth century. Sir Archibald Geikie, head of the Geological Survey of Great Britain, published his *Founders of Geology* in 1905. He celebrated the achievements of British geologists, especially the Scots James Hutton and Charles Lyell. He arranged his history around battles between Neptunists and Plutonists and Uniformitarians and Catastrophists. Karl Zittel, a professor at the University of Munich and a renowned paleontologist, published a *History of Geology and Paleontology* in 1901. He gave more weight to mineralogy, petrology, and theories of mountain elevation, and praised Suess as having achieved "almost general recognition for the contraction theory."

This celebration of geology's progress was soon to seem inappropriate. The cooling earth with its foundering continents did not survive as a synthesis for more than a decade. The discovery of radioactivity revealed a heat source within the earth that counteracted the cooling from some original molten state. The discovery of isostasy made it highly improbable that continents could have foundered. Detailed studies of the Alps made it clear that simple up-down forces acting on the earth's crust could not explain the tens or even hundreds of miles of foreshortening revealed by their folded strata.

The resultant theoretical vacuum led to a proliferation of alternatives in the 1910s and 1920s. Some scientists, such as Harold Jeffreys in England and Hans Stille in Germany, attempted to revamp contraction theory in light of the criticisms. Others preferred more radical alternatives: the planetismal hypothesis advanced by Thomas Chamberlin, the radiogenic by John Joly, and the theory of continental drift of Alfred Wegener. None of these theories succeeded in garnering enough evidential support to win widespread acceptance.

For the next fifty years, geologists hunkered down and continued their map-making and surveying. Mineralogy and petrology made important advances. Underwater exploration revealed interesting gravity anomaly patterns around island arcs. Geologists found new work in the oil industry, which joined geological surveys and mining as the main sources of employment outside the universities. The American Association of Petroleum Geologists, founded in 1917, had become the world's largest professional geological society by 2000, with over 30,000 members in more than 100 countries. By this time, however, geology was no longer the umbrella discipline for the study of the earth, but just one branch of the earth sciences.

RACHEL LAUDAN

GERM. The word "germ" derives from the Latin for "seed"; it was first used in its modern sense of pathogenic microbe in the nineteenth century. The theoretical association of "seed" with disease dates from antiquity but in modern times is associated with the *De contagione* (1546) of Girolamo Fracastoro. The development of the microscope in the early seventeenth century made possible the discovery of formerly invisible living creatures. Pioneering observations by the Dutch microscopist Antoni van Leeuwenhoek later in the century disclosed identifiable "animalcules" in various waters and on human teeth. The imperfections of most available optical instruments hindered further significant observations until critical improvements in the early 1830s. In 1835, Agostino Maria Bassi showed that a minute fungus caused muscardine disease in silkworms. Microbes soon were associated with many other diseases: Casimir Joseph Davaine, notably, repeatedly observed rod-shaped structures, which he named "bacteridia," in the blood of creatures dead of anthrax. The relationship between such structures and disease, whether cause or result, remained a matter of debate.

From the 1830s, European scientists interested in the processes of fermentation and putrefaction moved steadily towards the development of a germ theory of disease. In 1840, Jacob Henle set out the theoretical framework for such a theory, while Theodor Schwarnn demonstrated that not the air itself, but something in the air initiated putrefaction in organic substances. Louis Pasteur attracted popular and scientific attention when he announced his own germ theory of disease causation in 1864. The issue was widely debated in the following decade, until Robert Koch identified the causative organism of anthrax (1876), and later those of tuberculosis and cholera. Several recent historians have shown that several different germ theories of disease circulated in the later nineteenth century, most in a continual process of modification. Consensus was reached only around the turn of the century.

The contribution of Koch and his associates to the establishment of the germ theory extended beyond the identification of organisms. Koch drew up the program known as "Koch's postulates," which, through several subsequent revisions, continues in use as the basic tool for confirmation of an association between specific microbes and diseases. Koch and his colleagues made important contributions to the identification of bacteria by developing staining methods based on the new industrial dyes of the period, and by 1900 the bacterial causes of several dozen diseases had been established. At this time many physicians believed that every disease must have its causal bacterium. Increasingly too, they identified diseases not by symptom as in the past, but by cause, in the laboratory.

Improvements in bacterial filtration processes after 1880 led to the realization that there must be yet smaller disease-causing agents, and in 1896 Martinus Willem Beijerinck launched his controversial but valid concept of the filterable virus—possibly water-soluble microbes small enough to pass through filters and invisible to contemporary microscopes. Among the first pathogens identified as such were the agents of tobacco mosaic virus, foot and mouth disease, and yellow fever. Virology evolved rapidly as a science in the early twentieth century. The bacteriophage phenomenon was independently identified by Frederick William Twort and Félix d'Hérelle during World War I. Only with the invention of the electron microscope in the early 1930s, however, did it become possible to obtain visual impressions of viruses.

In the twentieth century, the idea of germs as disease agents became firmly established in the popular consciousness, partly through the use of the concept in advertising for domestic cleansing products. Virology remained a field of dynamic scientific interest; new or emergent virus diseases attracted attention across the twentieth century. The expansion of air travel, international trade, and global tourism alerted the medical community around 1970 to the possibilities of the diffusion of previously unrecognized and dangerous viruses.

At a more mundane level, Western countries became increasingly uneasy at an apparent upsurge in food-borne infections such as salmonellosis and listeriosis, which suggested the continuing threat to physical well-being of the endemic germs encountered in everyday life. In the last decades of the twentieth century, the discovery of prions—infectious dead proteins—forced a reassessment of the classic germ theory of disease, which was based on the belief in living disease organisms.

Anne Hardy

GLACIOLOGY is the discipline that examines how glaciers and ice sheets behave. It studies their origin and accumulation, deformation and movement, sublimation and melting, as well as how glacial ice interacts with climate. A subdiscipline of geophysics, glaciology also has strong ties to the atmospheric sciences, particularly climatology, and to glacial geology, which analyzes the history and geological effects of glaciers, glaciation, and ice ages. The study of mountain glaciers and polar ice caps has required mountaineering skills and other high-risk tactics, so the history of glacier exploration and examination is also a history of adventure and, in some cases, tragedy.

In the late eighteenth century, Horace Bénédict de Saussure and other naturalists began studying mountain glaciers in the Alps, descriptive work that was summed up by the Swiss naturalist Louis Agassiz in his *Études sur les Glaciers* (1840). In the mid-nineteenth century, James David Forbes began systematic observations of glacial flow, using physical theory in an attempt to understand the phenomenon. In the latter part of the century, John Tyndall's publications on glaciers and glaciation influenced both scientists and the public.

The first International Polar Year (1881–1883) was largely responsible for the first studies of high-latitude glaciers and ice sheets. Expeditions to Greenland directed by Fridtjof Nansen in the 1890s and by Alfred Wegener in the early 1900s surveyed the ice sheet. Robert Scott's Antarctic expedition of 1901–1904 conducted the first studies of the southern ice sheet. The renowned valley glaciers of southeast Alaska were first examined by Grove Karl Gilbert while on the Harriman Alaska expedition in 1899.

In the early twentieth century, R. M. Deeley and P. H. Parr made the first successful mathematical models of glaciers as viscous fluids. The first professional society for glaciology was founded in the 1930. In the 1950s—recognized within the field as the beginning of its modern era—John Nye led in putting glaciology on a sound physical footing. In the same decade the International Geophysical Year (IGY) (1957–1958) sparked further studies of high-latitude phenomena.

Current glaciological investigations are interdisciplinary and international. Ice sheets preserve one of the finest records of climate change over the last hundred thousand years or more. Among the notable discoveries of recent decades is that the ice record of atmospheric carbon dioxide content shows a marked positive correlation with fluctuations in global temperature. Fears of global warming have impelled scientists also to examine short-term behavior of these large ice sheets, which hold much of the world's water and hence have an important influence on global changes in sea level. Programs are in place for drilling and examining cores from the Greenland and Antarctic ice sheets. Other glaciologists are studying the rapid surging and retreat of ice shelves and of glaciers, the basal boundary condition of glaciers, and the interaction of glaciers with their substrates. The study of ice on other planetary bodies, notably on Jupiter's moons Europa and Ganymede, on Saturn's icy satellites, and on Triton, is an emerging field. Icy outer crusts on these bodies exhibit phenomena uncommon to Earth—impact cratering preserved in ice, and ice volcanism—eruption of liquid (probably water) through the icy crust.

Joanne Bourgeois

H

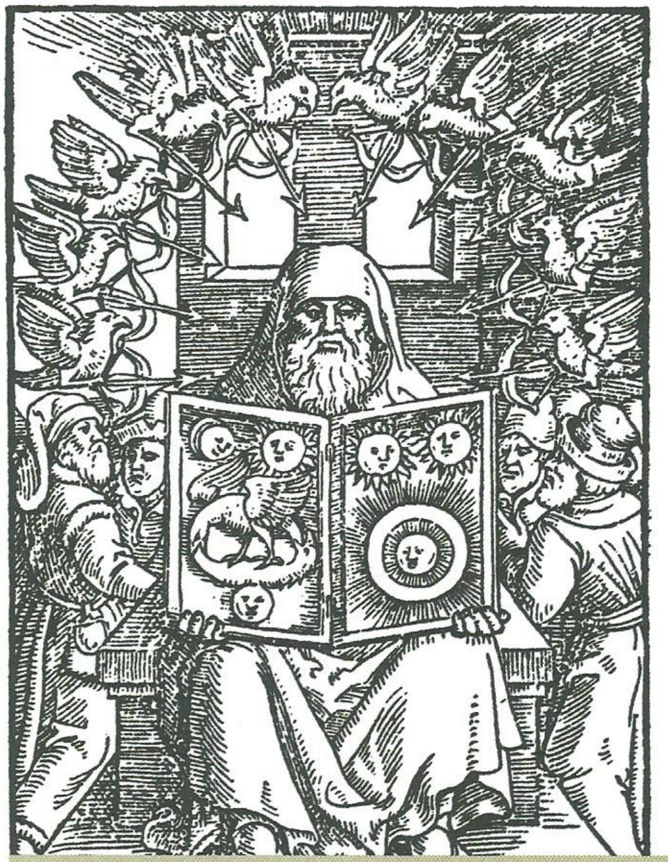
HERMETICISM. In 1462–1463, the Florentine Renaissance humanist Marsilio Ficino translated into Latin a Byzantine collection of treatises known collectively as the Hermetic Corpus. His translation, for which he interrupted his life work of translating Plato and Plotinus, introduced hermeticism, hitherto known only by a few fragmentary texts and references, to European philosophers. For two centuries, Hermetic Corpus and associated texts fascinated humanists and philosophers. They believed them to be of great antiquity, written by a younger contemporary of Moses, the Egyptian sage known as Hermes Trismegistus, an alias for the Egyptian god of wisdom and knowledge, Thoth. In 1614, the scholar Isaac Casaubon threw cold water on this reverent attitude by concluding from textual analysis that the Hermetic Corpus, far from being one of the earliest texts of revealed religion, was a much later compilation. His conclusions held up. By the end of the seventeenth century hermeticism was in precipitous decline. Today scholars believe that members of eclectic, gnostic religious groups in Egypt wrote the texts in the first and second century A.D.

The Hermetic Corpus dealt primarily with religion. It inspired the hope in Renaissance scholars that it might be a guide to the Prisca Theologica, the ancient theology, and would thus serve, depending on the point of view of the scholar, to replace Christianity or to strengthen it by extending the repertoire of revealed religion. Some texts, however, considered how the wise could come to understand and control the correspondences between the macrocosm and the microcosm. They discussed astrology, alchemy, and the signatures of plants.

Marsilio Ficino and his associate Giovanni Pico della Mirandola assimilated hermeticism to two other intellectual traditions, Neoplatonism, and natural magic. Magic has been practiced in many human societies and in broad outline everywhere depends on similar assumptions. Magicians assume that the powers by which one thing in the world affects another are hidden or occult. They can be discovered, and thus controlled, only with difficulty, usually by the magician who has special insights because of his preparation, as much spiritual as intellectual or practical.

Two kinds of magic can be distinguished: spiritual and natural. In spiritual magic, the magician prevails upon the spirits, good or bad, white or black, to set in motion these occult powers. In natural magic, the magician relies on detecting correspondences and signatures in the natural world. Renaissance humanists and philosophers distanced themselves from spiritual magic, a touchy matter that quickly led to trouble with the church. They pursued instead a dignified version of natural magic. Since both magic and Neoplatonism had contributed to the synthesis of the Hermetic Corpus, Ficino and Pico did not have far to go to assimilate it to the versions of magic and Neoplatonism current in their own time. Giambattista della Porta, the most famous exponent of natural magic, published his *Magia naturalis* (Natural Magic) in 1558. Much of it dealt with the "magic" of mechanical gadgets, secret writing, and cosmetics.

Positivist historians of science naturally viewed this amalgam of hermeticism, natural magic, and Neoplatonism as inimical to the growth of modern science. Those not wedded to that tradition thought otherwise. The distinguished American historian Lynn Thorndike wrote his monumental *History of Magic and Experimental Science* (8 vols., 1923–1958) to demonstrate that magical tradition, with its utilitarian attitude to the world that contrasted strongly with the contemplative attitude of philosophers, spawned the method of experiment. The German physician and historian Walter Pagel, in a series of scholarly studies from the 1930s through the 1960s, showed how the hermetic traditions shaped the work of chemist-physicians such as Paracelsus (c. 1493–1541) and Jean Baptiste van Helmont (1579–1644). From there, certain hermetic and Neoplatonic ideas passed into chemistry and mineralogy and were revived in the late eighteenth century by the founders of Naturphilosophie.



Hermes Trismegistus, supposed ancient Egyptian author of texts on alchemy and magic, as depicted in Zadith ben Hamuel, *De chemica senioris* (1566)

In 1964 the historian Frances Yates made strong claims that hermeticism had affected not just certain methods or particular chemists but was one of the basic causes of the Scientific Revolution. Her thesis appeared when historians of science sought new interpretations of the formative period of modern science. Those who followed up her suggestions found that hermeticism in particular (as opposed to Neoplatonism) had been most influential in the theory of matter—whether in chemistry or in natural philosophy. Some historians of science continued the Pagel project. Others argued that Isaac Newton, who labored over alchemical and hermetic works for years, may have found in them support for his ideas of attraction and repulsion, traditionally regarded as occult properties. Later it was suggested that music mediated the domains of magic and experimental science and that musical practices informed natural philosophy. As the features of music thought to be occult were understood through experimentation, natural magic began to yield to science. Today few historians of science would doubt that hermeticism had an important role to play in the genesis of modern science though just what role and just how important a role have not been decided.

RACHEL LAUDAN

HIGH-ENERGY PHYSICS. The field of high-energy physics emerged after World War II out of research in nuclear physics and cosmic ray physics. Its name referred to the energies of the nuclear and subnuclear particles that physicists sought to study, and hence the field was also sometimes called elementary particle physics.

Physicists in the first decades of the twentieth century used particles emitted by radioactivity as a probe of the atomic nucleus. But many of the charged alpha and beta particles emitted in natural radioactive decay had insufficient energy to overcome the electrical barrier of the nucleus, and exist in insufficient quantities to provoke enough reactions for convenient study. Starting in the 1920s, nuclear physicists sought to increase the energy of the particles by accelerating them. Early accelerators passed electrically charged particles through a single large voltage drop (as in the Cockcroft-Walton and Van de Graaff accelerators) or multiple, smaller drops provided by high-frequency oscillators (as in the cyclotron and linear accelerator, or linac) to kick particles to higher speeds. Technical refinements and industrial-size apparatus allowed particle accelerators to produce ever higher energies through the 1930s, beyond ten million electron volts.

In the meantime, starting in about 1930, physicists began to exploit a natural source of high-energy particles in cosmic rays. A thriving field of cosmic ray research focused on sorting the nature of cosmic radiation as well as new phenomena and new particles, including the positron (detected in 1932 by Carl David A. Anderson) and a mysterious new particle with mass midway between that of the electron and proton, which was hence called the meson. Whereas nuclear physics in the 1930s emphasized the particle accelerator, cosmic ray research relied on particle detectors, especially cloud chambers and Geiger counters.

World War II interrupted the pursuit of high-energy particles but provided new resources, both technical and political, to exploit after the war. Technical resources included advances in microwave electronics and new designs for accelerators, both of which allowed physicists to push into energies of billions of electron volts. By about 1950, physicists could perceive some separation between nuclear physics and a new subfield of particle physics, which became known as high-energy physics.

New political resources stemmed from the contributions of physicists to military technology during World War II and their continued mobilization during the Cold War. National governments supported high-energy physics as a way to train new scientists and engineers who might then work on problems of national interest; as a means to keep talented scientists on tap in national laboratories in case of military emergency; and as a hedge against scientific discoveries that might have military or industrial applications. High-energy physics also provided a surrogate arena for international competition, with American, Soviet, and European labs jockeying for the claim to high-energy hegemony. High-energy physicists accepted and encouraged such justifications of state support, in exchange for the opportunity to pursue interesting and challenging scientific problems at higher energies.

Postwar high-energy physics combined detectors and accelerators in laboratories that typified a new type of big science, characterized by large and expensive equipment, state support, cooperative team research, collaboration of scientists and engineers, and industrial-style management. American laboratories led the postwar development of big-science accelerator programs, notably at the University of California at Berkeley and Brookhaven in New York, although the Soviet Union and a new European lab at CERN soon offered strong competition. The United States in the 1960s would choose to centralize its largest accelerators in a new lab at Fermilab near Chicago, which would thereafter challenge CERN for the claim to the highest energies.

High-energy physics had theoretical and experimental components. Experimentalists pushed toward higher energies, lured by the possibility of producing previously unseen particles with masses equivalent to the energy of particle collisions. In 1955, Berkeley scientists achieved the exemplary discovery of the antiproton using the first generation of postwar accelerators. Higher energies required ever larger magnets and vacuum chambers and bigger budgets, all of which constrained the ambitions of accelerator builders. The invention of strong focusing in 1952 provided a way around the problem of magnets and vacuum volumes, both of which contributed to costs. The principle used an alternating gradient in the magnetic field to compress the beam of particles, and quickly led to proposals from Brookhaven, where the idea originated, and CERN, whose design problems had inspired the Brookhaven work, for machines in the range of 25 billion electron volts.

Physicists still needed ways to study the output of accelerators, and particle detectors grew in importance and size in the 1950s and beyond. They fell into two general categories. Image detectors, such as cloud and bubble chambers and nuclear emulsions, produced a snapshot of the tracks left by individual particles at a particular time and place. Logic devices, such as electronic counters, accumulated statistical counts of large numbers of particles. By the 1970s, physicists were combining the two types in new, even larger detectors.

Experiment led theory in high-energy physics through the 1950s, as theorists struggled to explain new resonances and particles emerging from accelerators. To make sense of the proliferating particles theorists classified them according to such properties as strangeness and isospin; then, in the 1960s, theorists developed the quark model of matter to resimplify the concept of fundamental particles and began to seek a unified theory of the four fundamental forces that would incorporate the quark model. By the 1970s, theory was driving experiment, as particle physicists directed their research to find particles predicted by the new theories. Their efforts paid off in the detection of the J/psi and W and Z particles, weak neutral currents, and several of the postulated quarks, thus confirming the so-called standard model of the theorists and encouraging speculation about a grand unified theory, or theory of everything.

The spiraling energies available in accelerators changed the definition of high energy. Accelerators that had pushed back the high-energy frontier in the late 1940s were considered medium-energy machines by the mid-1960s; succeeding generations of devices might last only a decade or so at the cutting edge. Theorists, in the meantime, extended their equations far beyond energies available in the laboratory or in nature, and particle physics began to merge with cosmology; the phenomena postulated by theorists existed only in the milliseconds after the Big Bang and disappeared as the universe expanded and cooled.

Scientific and popular attention to the quest of particle physicists made theirs the most glamorous field of physics in particular, if not science in general, in the second half of the twentieth century. High-energy physicists claimed to engage in the most fundamental research, from which all other science was derived, since they dealt with the elementary constituents of matter. Physicists in other fields, such as solid-state physics, questioned the pretensions of particle physicists and sought to divert some of their substantial government funding. The perceived fundamental nature of high-energy physics alone could not ensure continued state support, especially after the end of the Cold War. American physicists in the 1980s proposed a massive new accelerator, the Superconducting Super Collider (SSC), to pursue the Higgs boson and other exotic phenomena predicted by theory in the neighborhood of 40 trillion volts. In 1993, the U.S. Congress voted to end the multi-billion dollar project, unconvinced that the scientific results justified the social investment.

PETER J. WESTWICK

HOMEOSTASIS. The American physiologist Walter Cannon coined the word "homeostasis" in 1926 to designate the coordinated physiological reactions that maintain steady states in the body. He believed that a special term was necessary to differentiate the complex arrangements in living beings, involving the integrated coordination of a wide range of organs, from the relatively simple physico-chemical closed systems in which a balance of forces maintains an equilibrium. "Changes in the surroundings," Cannon wrote, "excite reactions in [the open system that constitutes a living being], or affect it directly, so that internal disturbances of the system are produced. Such disturbances are normally kept within narrow limits, because automatic adjustments within the system are brought into action, and thereby wide oscillations are prevented and the internal conditions are held fairly constant."

Cannon illustrated his concept by describing a variety of mechanisms that maintain constant conditions in the fluid matrix, or "internal environment," of higher animals. These included materials such as glucose and oxygen in the blood, as well as the fluid matrix's temperature, osmotic pressure, and hydrogen-ion concentration. The knowledge of the mechanisms that Cannon showed to be involved in these reactions came largely from his own previous experiments on the role of the autonomic nervous system and the adrenal secretions. The close association he established between homeostatic mechanisms and the preservation of conditions in the internal environment, however, derived in large part from the inspiration of the nineteenth-century French physiologist Claude Bernard, whom Cannon acknowledged as the first to give a "more precise analysis" to general ideas about the stability of organisms. Cannon quoted particularly Bernard's "pregnant sentence" that "It is the fixity of the 'milieu interieur' which is the condition of free and independent life."

Originally a physiological principle, homeostasis took on broader meanings after World War II, with the recognition of the similarity of homeostatic mechanisms to feedback controls in servo-mechanisms. Biologists applied the concept at all levels—cellular, organ system, individual, and social systems. The maintenance of steady concentrations of the intermediates of a metabolic pathway despite a constant flux of matter and energy through the pathway became an example of homeostatic regulation. Cannon himself had asked in 1932 in his popular book *The Wisdom of the Body,* in an epilogue entitled "Relations of Biological and Social Homeostasis," whether it might not "be useful to examine other forms of organization—industrial, domestic, or social—in the light of the organization of the body?" His suggestion has been followed, and homeostasis in its widest sense now means the "maintenance of a dynamically stable state within a system by means of internal regulatory processes that counteract external disturbances of the equilibrium."

FREDERIC LAWRENCE HOLMES

HORTICULTURE. From the earliest times plants have been subject to utilitarian and commercial enterprise. Herbalists and apothecaries regulated the supply of medicinally useful plants to customers, while sailors and merchants took considerable risks to import valuable spices and exotics. Horticulture, however, implies the development and marketing of desirable plant commodities and as such essentially dates from the Renaissance. There are few clearer-cut examples of the long-term manipulation of natural organisms for fashion and changing human tastes.

The diversification of the eight classic florists' flowers—the auricula, polyanthus, hyacinth, anemone, ranunculus, tulip, pink, and carnation—dates from the sixteenth century. Of these, the tulip was the most important. Bulbs reached Vienna from Turkey in 1554, although they probably circulated well before that date. The plant was rapidly subjected to improvement, especially in the "breaking" or striping of the petals. Many different varieties appear in Dutch and Flemish still lifes of the seventeenth century. The production of tulip bulbs and their commerce became highly professional; monasteries provided most of the bulbs sold across Europe. In the 1630s, the Dutch suffered tulipomania, called by them the "Wind trade." The market crashed in 1637.

During the eighteenth century, the rise of botanical gardens and interest in landscape gardening and the embellishment of the great estates of Europe led to a marked increase in horticultural activities. Glasshouses and hothouses of various kinds came into use. But the real growth of commercial horticulture came in the early nineteenth century as a consequence of the industrial revolution, with easier and cheaper glass production, the repeal of glass taxes in Britain, new distribution networks like the railways, and the development of coal-fired stoves, flues, and ventilation systems. Suddenly, nursery workers could contemplate mass-production of plants. There was a marked surge in commercial nursery firms and seed producers during the nineteenth century, two of the most important being the

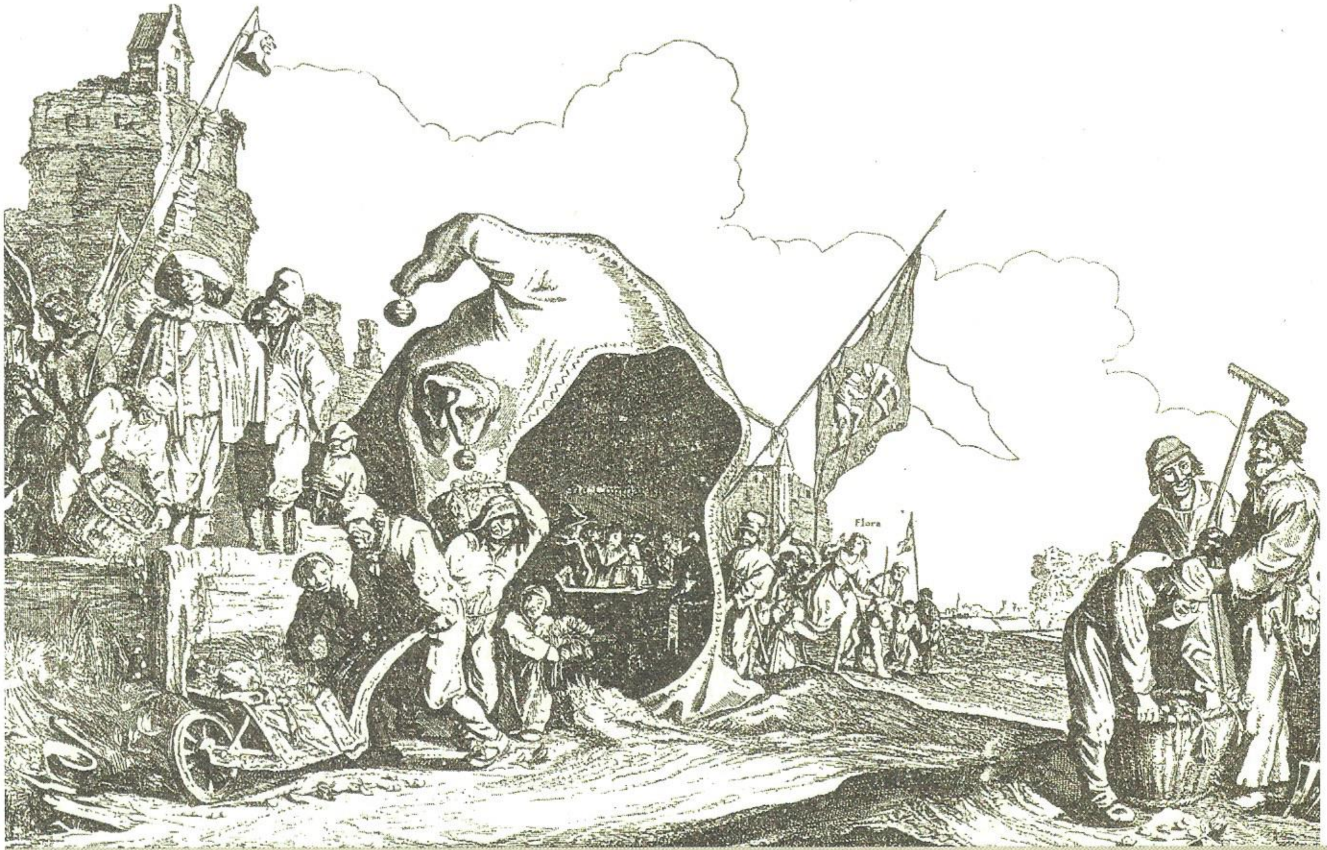
Vilmorin Company in Paris and James Veitch in England. Garden flowers, vegetables, vines, and fruits became highly diversified. Charles Darwin said that he grew fifty-two varieties of gooseberry alone. Public gardens began to include serried ranks of identical, brightly colored flowers laid out in formal bedding schemes. John Claudius Loudon and his wife, Jane, fuelled popular interest with gardening manuals and the first garden magazine. Flower shows and societies also played a part, such as the Horticultural Society of London (founded in 1805, later the Royal Horticultural Society) with grounds in Chiswick, London. This society began the practice of awarding medals and certificates for choice specimens at their annual show. It especially encouraged the commercial development of orchid breeding.

Diversification continued rapidly through the early twentieth century. Practical expertise inter-meshed increasingly with plant genetics, as at the John Innes Institute for Plant Breeding in Norwich, which played a central role in advancing the field. Toward the end of the century technological advances allowed highly sophisticated propagation techniques. The botanist William Stearn introduced the word "cultivar" to distinguish plants of human-made origin from real varieties.

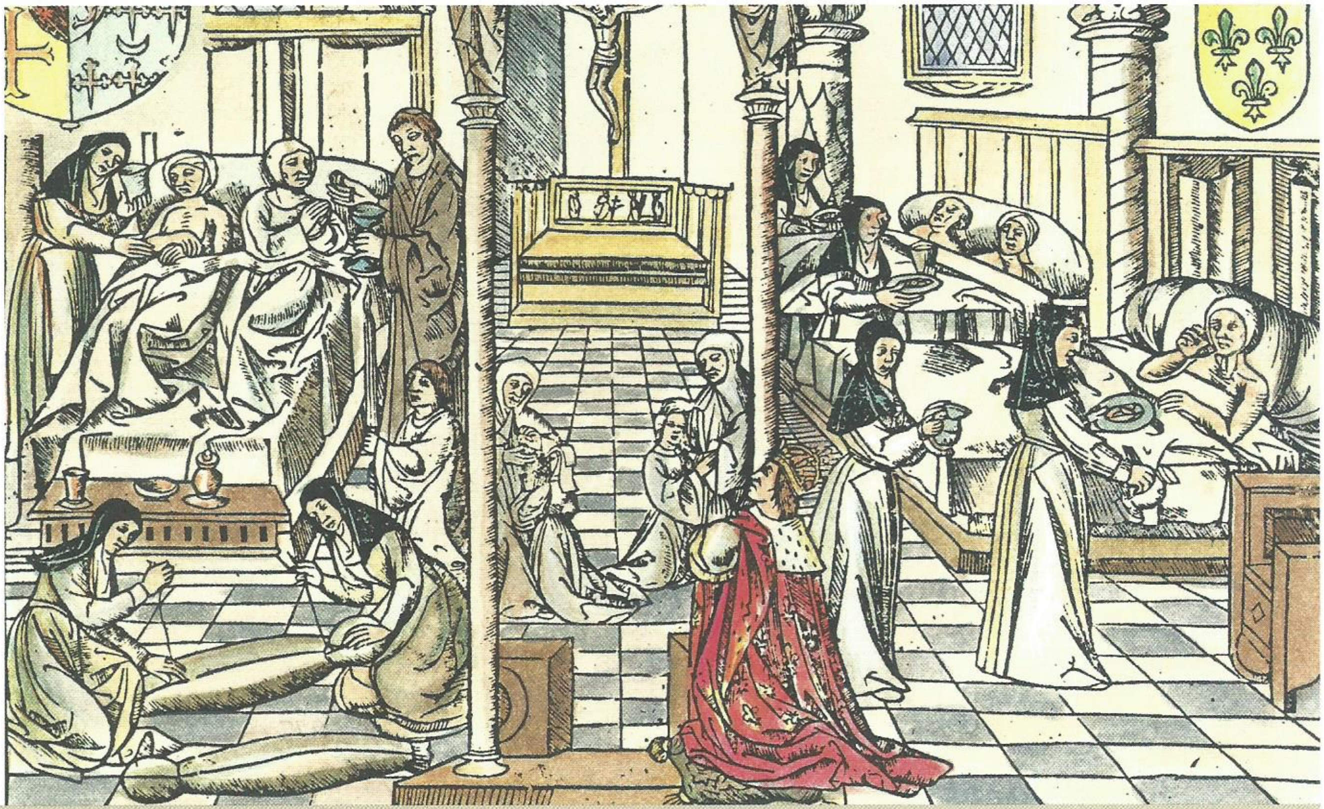
JANET BROWNE

HOSPITAL. The traditional charitable role of the hospital was to provide shelter and food as well as spiritual salvation and bodily recovery in times of famines and epidemics. Reflecting a more positive vision of health and the new mercantile economy, young urban workers, their livelihood threatened by illness, sought hospital care during the Renaissance. By the early 1500s, this shift prompted a regular medical presence, exemplified by conditions at the Santa Maria Nuova Hospital in Florence. Physicians medicalized hospitals they visited, experimenting on patients with established and new remedies and preserving their newly gained experience in casebooks. They also created disease classifications, occasionally instructed medical students, and subjected deceased and unclaimed inmates to anatomical dissection. By the 1730s, European hospitals were primarily places for physical restoration of the military and civilian labor force. Providing Enlightenment physicians with greater access to wide sectors of the population, hospitals became ideal settings for an expanding medical presence. They provided the necessary context for the construction of a new medical science and improved clinical skills, nurseries capable of training better medical professionals. Some hospitals offered programs of institutional apprenticeship for surgeons (at the Hôtel Dieu of Paris) and for physicians (at British voluntary institutions such as St. George's Hospital in London and the Royal Infirmary of Edinburgh). John Aikin, who considered the hospitalized sick poor as ideally suited for "experimental practice," and John Howard, a widely traveled prison and hospital reformer, were early leaders of this hospital movement.

The conversion of hospitals into instruments of medicine acquired greater momentum in the nineteenth century. European hospitals linked to local universities such as Guys Hospital in London, the Hôpital de la Charité in Paris, and the Allgemeines Krankenhaus in Vienna became sites for comprehensive programs of education and research. Notable early proponents of hospitals as medical institutions were the French physicians Pierre J. G. Cabanis and Jacques-René Tenon. With their numerous halls filled with the sick poor, large hospitals were veritable museums of pathology. In these controlled environments, physicians took advantage of the diversity of illnesses and funneled interesting cases



A Dutch cartoon from 1637 lampooning "tulipomania," the wild speculative trade in tulips that crashed that year



The interior of the Hotel de Dieu, Paris, ca. 1500. Sewing up the shrouds of the dead within view of the dying might not have been comforting.

into special teaching units for detailed studies and experimental management.

Clinical knowledge obtained in the wards was focused overwhelmingly on acute, complex, and life-threatening conditions. This institutional environment came to shape the character of Western medicine: dramatic, disease oriented, and interventionist, in effect removing sick individuals from medical cosmology and replacing them with depersonalized disease carriers. By contrast, the largely patient-dominated context of private practice continued to shape knowledge and treatments related to more common health problems and chronic conditions. In the end, the hospital context was decisive in grounding and framing biomedical medical care.

Changes in welfare schemes and professional power relationships, educational expediency, and innovation all contributed to the reform of the traditional hospital. In the early 1800s, novel ways of practicing medicine in Paris attempted to solve the dual problems of large numbers of institutionalized sick and severe manpower shortages among attending physicians. These new techniques, pioneered by French physicians including Philippe Pinel and T. R. H. Laennec, codified the disease manifestations of individual suffering inmates, including bodily clinical signs and anatomical changes. This "medicine of observation" thus became the main tool for acquiring professional knowledge: systematic study and classification of diseases and post-mortem dissection of deceased patients. Diagnostic specificity and outcome were achieved through the establishment of clinical-anatomical correlations. A new paradigm localized all bodily suffering in organ systems. As the product of social and political factors linked to the French Revolution and its wars, this new anatomical-pathological knowledge came to characterize the Paris Medical School. Eventually it spread throughout the world. The pathological paradigm—disease must have an identifiable anatomical seat—continues to rule biomedicine by consensus of its practitioners, and remains largely responsible for the professional solidarity among scientifically trained physicians, especially by contrast with practitioners of alternative medicine.

Sanitary considerations and medical knowledge, in turn, profoundly influenced hospital architecture and organization, the role of caregivers, and patient management. Hospital space was divided into separate pavilions and provided with improved heating and ventilation, practices pioneered in the 1880s by John Shaw Billings during the construction of the Johns Hopkins Hospital in Baltimore. Also in the United States, Edward S. Stevens and Isadore Rosenfield were among influential twentieth-century architects whose designs facilitated internal hospital circulation and greater patient privacy.

By the late nineteenth century, the strict separation between administration and caregivers, including physicians and nurses, remained. Physicians had the power to admit and discharge patients, substituting criteria based on medical needs for previous religious and charitable yardsticks. The work of nurses, professionally trained on the model established by Florence Nightingale, became an able extension of medical management. Total immersion, peer control, and behavioral guidelines were demanded of all institutional caregivers, forging stronger professional bonds through the creation of hospital instruction programs such as internships and residencies.

For the past two centuries, hospitals have remained ideal locations for the most advanced clinical research, teaching, and patient management of acute medical conditions. Hospitals also function as testing grounds for new technological devices, starting with instruments such as the stethoscope, ophthalmoscope, and laryngoscope, and continuing with forms of imaging from X rays to body scans. Beginning in the 1820s, many of the clinical characteristics observed in particular groups of patients underwent quantification and statistical manipulation, thereby exposing the probabilistic nature of clinical diagnosis and prognosis. The growing body of knowledge of patient outcomes became an increasingly valuable tool for judging the efficacy of medical treatments, especially after the employment of random clinical trials following World War II. And most of the therapeutic revolution of the last half-century took place in hospital settings affiliated with academic medical centers.

GUENTER B. RISSE

HUMAN GENOME PROJECT. The human genome project originated in the latter half of the 1980s in the United States. Its goal was to map the location of the 80,000 to 100,000 genes that human beings were thought to possess and to sequence the three billion base pairs that human DNA was estimated to contain. Recent technical developments had encouraged biologists to consider the mapping and sequencing effort a practical possibility. Human DNA had been found to include numerous restriction fragment length polymorphisms (RFLPs), so called because they were snipped from DNA by restriction enzymes and varied in length. Seemingly ubiquitous in the genome, they could provide numerous points of reference for gene mapping. Moreover, techniques for rapidly sequencing DNA had been incorporated into commercially available machines. At the then-current sequencing price of about one dollar per base pair, the cost of sequencing the entire human genome would come to three billion dollars. Enthusiasts of the human genome project needed government funding.

In the United States, they found it initially in the Department of Energy (DOE), which had a long-standing interest in the mutational impact of nuclear radiation on genomes. In 1987, DOE initiated an ambitious five-year human genome program that would comprise among other activities the development of automated high-speed sequencing technologies and research into the computer analysis of sequence data. The National Institutes of Health (NIH) quickly joined the genome game, if only to take principal control of it away from the big science—oriented Department of Energy. However, the increasing NIH commitment to the genome project stimulated opposition within the biomedical scientific community. The dissenters feared that the genome project would be a three-billion-dollar big science crash program, built around a few large bureaucratized centers that would be given over to DNA sequencing. The project would be tedious, routinized, and likely to sap resources from meritorious areas of biology.

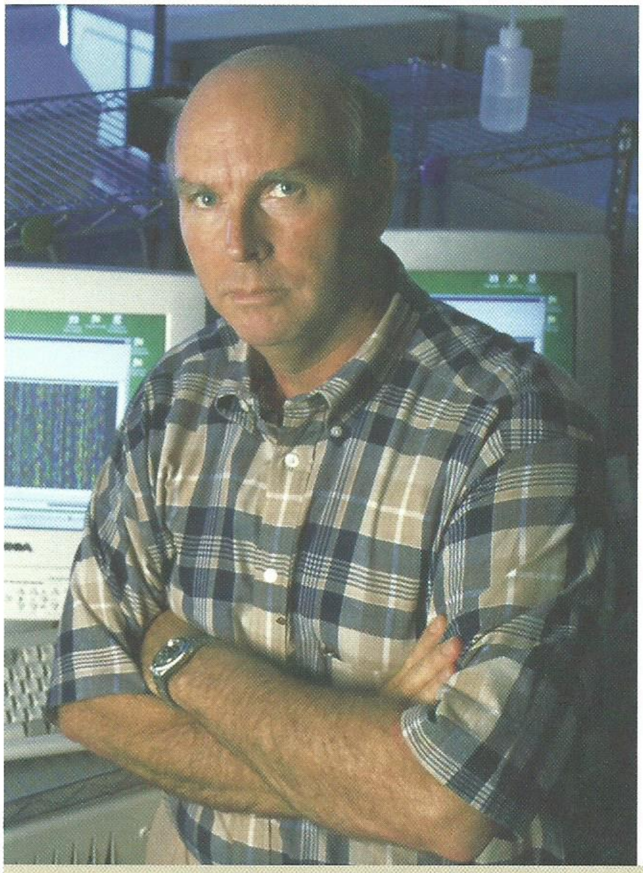
A coalition of genome enthusiasts and skeptics nevertheless found common ground in a genome project that would be spread over fifteen years and would serve a broad biological interest by sponsoring genomic investigations of nonhuman organisms such as mice and yeast. The project would speed the search for genes related to disease (a type of research that many biologists wanted to pursue anyway). Part of the money would be invested in the development of technologies that would make sequencing rapid and cheap enough to be accomplished in many ordinary-sized laboratories rather than in just a few large facilities.

Biomedical scientists and industrial representatives stressed to Congress that the project promised high medical payoffs and would be essential to national prowess in world biotechnology, especially if the United States expected to remain competitive with the Japanese. In October 1988, James D. Watson, the codiscoverer of the structure of DNA, was appointed head of what soon came to be called the National Center for Human Genome Research in NIH. The move effectively decided in favor of NIH the nagging issue of the lead federal agency in the biological side of the project; DOE would deal primarily with technology.

Following the United States, Britain, France, Italy, several other nations, and the European Community established projects to map and sequence at least parts of the human genome. In 1988, the Human Genome Organization was established as an international body—a "U.N. for the genome," one biologist remarked—intended to foster collaborative efforts and the exchange of information. Both the NIH, at Watson's initiative, and the European Community, at the behest of the European Parliament, incorporated into their respective genome projects investigations of the ethical, legal, and social issues in human genetics—for example, eugenics and the privacy of genetic information. The project was the first in the history of science with a mandate to deal with such matters.

Through the 1990s, genomic data poured out of laboratories on both sides of the Atlantic and into centralized databases, including one at the European Molecular Biology Laboratory, another at the Los Alamos National Laboratory, and still another at NIH's genome center in Washington. Late in the decade, the databases were made easily and freely accessible on the new World Wide Web.

Profit-making competition entered genomics in 1992 when Craig Venter, a specialist in gene sequencing at NIH, left to head a new private center called The Institute for Genomic Research (TIGR). Although TIGR would be nonprofit, it was funded by a venture capital group that established Human Genome Sciences Inc. to develop and market



Dr. Craig Venter, president of Celera Genomics, with machines for sequencing DNA

Alexander von Humboldt (1769–1859), German naturalist, traveler, and statesman, in his library

products resulting from TIGR's research. Venter predicted that TIGR would track down one thousand genes daily and would identify the majority of human genes within three to five years. In 1998, Venter moved to a new, for-profit company called Celera that aimed to sequence the entire human genome by 2001 using rapid new automated machines supplied by its principal owner, the Perkin-Elmer Corporation. Goaded by Celera, the NIH genome center picked up its sequencing pace. In June 2000, at a White House ceremony presided over by President Bill Clinton, Venter and Francis Collins, the head of the NIH project, announced that they had both completed a full draft of the human genome.

Despite the triumph, the entrance of profit-making companies into wholesale gene-sequencing worried leading biomedical scientists. The companies, led by Celera, have proposed to patent large fractions of the human genome without knowing much more about them than their base-pair sequences. Their strategy stimulated a forceful statement in 2000 by the presidents of the Royal Society of London and the National Academy of Sciences in the United States stressing that "the human genome itself must be freely available to all humankind." Offsetting the drive to privatize the genome are the freely accessible databases to which the public projects and their grantees in the United States and Europe are steadily contributing, but how much of the genome will be locked up by private corporations depends on the policies of the world's patent offices.

DANIEL J. KEVLES

HUMBOLDTIAN SCIENCE. Historians use the term "Humboldtian science" to describe a type of scientific practice during the nineteenth century that resembled the work of Alexander von Humboldt, whether or not it resulted from Humboldt's direct influence. Susan Faye Cannon coined the term in 1978 to signify a scientific style that conducted observations with the latest instruments, corrected measurements for errors, and linked these to mathematical laws; constructed maps of isolines connecting points with the same average values; identified large, even global, units of investigation; and used nature rather than the laboratory as a site of investigation. The term, as applied to nineteenth-century science, has since acquired other connotations, including connecting different types of large-scale phenomena, demonstrating their interdependencies, seeking a universal science of nature, and using large-scale international organizational structures to execute local readings as part of a global effort.

Scholars since Cannon have been careful to differentiate what Humboldt did from Humboldtian science. Humboldt deliberately avoided speculation and description as was found in natural history and natural philosophy. The major theme of his master science of terrestrial physics was the equilibrium of the earth's forces. For Humboldt, isolines represented not merely average values, but also a natural aesthetic order (as they did in patterns of maximum areas of concentration in the regional distribution of plants) and even political stability. This aesthetic sensibility rarely appears in Humboldtian science despite its importance to Humboldt, who in many ways incorporated the Romantic emphasis on aesthetics, the imagination, and the picturesque in image and word. Nature was to Humboldt not only the assemblage of averages and the balance of forces, but also an aesthetic composition. The language of his travel books projected strange worlds in living color, a literary quality with great public appeal. He also wanted to retain in nature study the morally didactic qualities that eighteenth-century aesthetic theory had valued. In this sense, Humboldt's science, in contrast to Humboldtian science, was not merely knowledge to be learned, but to be lived. Hence some of the social values associated with the "European tour" in the nineteenth century came from their association with Humboldt's science.

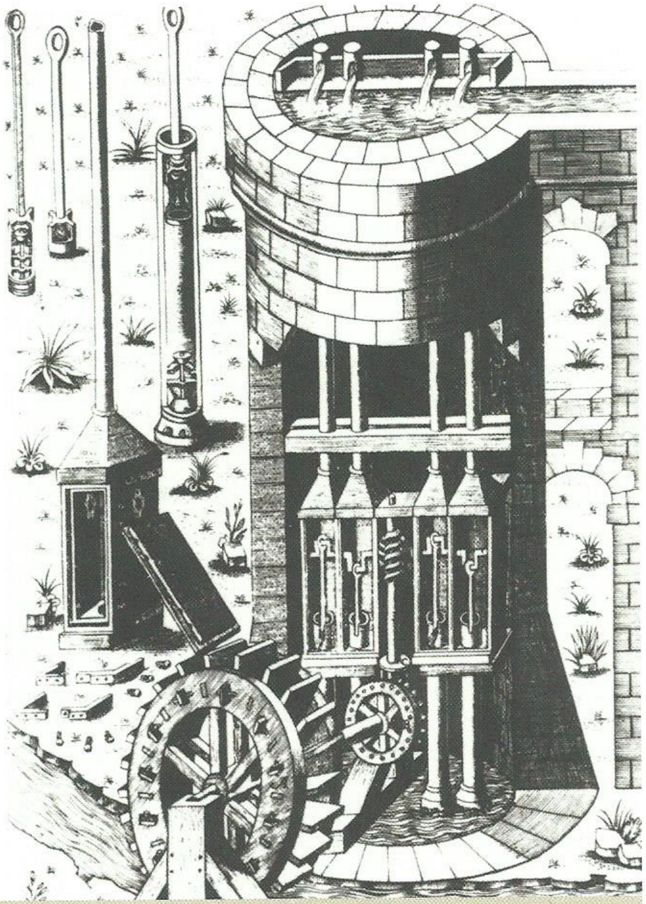
Humboldtian science, as it has been used, also does not include two diametrically opposed directions in which Humboldt's work was taken: popular science and disciplinary specialization. The aesthetic image of the unity and balance of nature's forces particularly appealed to the public. The theme of harmony in Humboldt's work acquired political, social, and religious connotations, and helped to make nature study a part of liberal culture in Germany. The image of nature's order became an antidote to social and political disarray after the European revolutions of 1848. Immediately following Humboldt's death in 1859, Humboldt Associations, and later Humboldt Festivals, were established throughout the German states. They promoted interest in nature through public participation in nature walks and specimen collecting. More focused disciplinary uses of Humboldt's work appeared after industrialization exuded pollution, damaged forests, and in other ways highlighted the interconnectedness of environmental conditions. August Grisebach published in 1872 the first comprehensive classification of the earth's vegetation according to climatic conditions in which he adopted Humboldt's techniques in plant geography, especially Humboldt's notion of "social plants" (plant species in a regional environment forming special communities, such as heaths, savannahs, and bogs, that excluded the germination of other species).

Humboldtian science differed markedly from the institutionalized, disciplinary-based sciences that took shape in the nineteenth century. Although Humboldtian science shared the methodological rigor of nineteenth-century scholarship *(Wissenschaft),* it eschewed the intellectual specialization of, and sharp divisions between, scientific disciplines. For example, Humboldt and his Berlin colleague the physicist Heinrich Wilhelm Dove took meteorological measurements, but Dove's meteorology never reached out to other scientific disciplines like botany and never included naturalistic drawings in color. Dove also conducted some of his experiments in a laboratory; a Humboldtian scientist worked only in nature. The laboratory scientist posed detailed, particular questions in a contrived environment where certain variables could be held constant. Practitioners of Humboldtian science viewed nature as an ensemble, an organic whole whose interrelatedness could be captured in a geography broadly defined and keenly sensitive to large-scale issues. British natural philosophers especially viewed Humboldtian science as a rigorous counterbalance to the specialization and professionalization then shaping the content and practice of science.

Despite its marginal institutional position, Humboldtian science had a powerful effect on certain areas of science in the nineteenth century, especially geomagnetism, as well as on the development of certain scientific communities. Historians have found Humboldtian science more in evidence in Anglo-Saxon regions than elsewhere. Humboldtian science appeared most frequently in Victorian Britain with its vast empire over which scientists could collect data on the scale advocated by Humboldt. The best example of Humboldtian science is the British Magnetic Crusade, an effort dedicated to measuring the magnetic features of the earth in the British empire and beyond. Humboldt himself had proposed to the Royal Society of London that its members undertake global geomagnetic observations; in the 1830s the British government donated over £100,000 to the enterprise. Directed by Humphrey Lloyd of Trinity College, Dublin, the Magnetic Crusade consisted of a chain of fixed magnetic observatories with standardized instruments whose measurements—magnetic declination and the horizontal and vertical components of magnetic intensity—were sent to England where Edward Sabine reduced them. Methods of observation were printed on instruction sheets and distributed; adherence to the rules of observation was upheld by naval officers who conducted many of the observations. Through these observations Sabine could correlate deviations in Earth's magnetic phenomena to the action of sunspots and demonstrate the eleven-year cycle in sunspots.

The British viewed Humboldt as writing within their tradition of providential design in nature, and were annoyed that he did not specify the design's spiritual agency. Yet they believed that Humboldt's measuring methods were suited for shaping character and tempering laziness in young men. Humboldtian science defined the work of two leading British scientific organizations, the Royal Society of London during the 1820s and the British Association for the Advancement of Science in the 1830s. British imperial activity also bore the mark of Humboldtian science. Charles Darwin carried a copy of Humboldt's *Personal Narrative* aboard the voyage of HMS *Beagle* from 1831 to 1836. Humboldt's aesthetic image of nature recurs in the paragraphs on the tangled bank near the end of Darwin's *Origin of Species* (1859). In Australia magnetic observations at the Rossbank Magnetic Observatory between 1840 and 1854 and astronomical ones at Melbourne's Flagstaff Observatory (founded 1857) were further examples of Humboldtian science. The Ross-bank data became Australia's first project in physics, inspiring a younger generation, including Georg Neumayer, the German scientist who founded the Flagstaff Observatory. In characteristic Humboldtian fashion, Neumayer gathered data from remote locations for map construction by means of the telegraph. British colonial administrators believed Humboldtian science was a part of their "civilizing mission." Even British imperial literature captured its importance. Rudyard Kipling's *Kim* (1901) not only immortalized the empire's penchant for gathering data on natural and human activity (Colonel Creighton was an ethnographer, Kim a surveyor), but also took place during the period of political unrest when natural and social data about India became a form of surveillance deployed to hold the empire together.

Elsewhere, Humboldt directly influenced the Berlin geographer Carl Ritter, but he, like other Humboldt-inspired German scientists, directed no large-scale projects. When Humboldt proposed to the British that they inaugurate global geomagnetic observations, he did not know that Carl Friedrich Gauss had already published a mathematical theory of magnetic intensity in 1833. Working with the physicist Wilhelm Weber, Gauss nonetheless made the Magnetic Observatory at the University of Göttingen (then a part of the British empire) the center of the British Magnetic Crusade. Gauss and Weber designed the instruments for the project, all chronometers were calculated, and all observations were reduced, according to Göttingen mean time. Neither Gauss nor Weber, however, held up Humboldt's work as a model; both continued to work within the framework of laboratory- or observatory-based disciplinary sciences.



An undershot water wheel driving water pumps via a worm gear and other machinery from Antonio Ramelli's *Le diverse et artificiose macchine* (1588)

Many other scientists, even among the British, felt that Humboldt's science led to writing in outmoded traditions of travel literature and that the integration it claimed was rarely achieved. In the context of discipline-building and professionalization in Germany, Humboldt's science came to be viewed as amateurish, a throwback to an earlier era. Humboldtian science of a sort did promote scientific internationalism, but to what degree is still disputed. Although a concept constructed by historians rather than by historical actors to explain their own actions, Humboldtian science seems to capture the sciences of empire.

KATHRYN OLESKO

HYDRODYNAMICS AND HYDRAULICS. From at least the third millennium B.C., canals, dams, and reservoirs were used for irrigation in Egypt, in Mesopotamia, and probably also in Asia. The building of these constructions and contemporary techniques of navigation imply some practical understanding of fluid motion. A greater theoretical knowledge and more elaborate apparatus appeared in Alexandria in the third and second centuries B.C. Archimedes established the laws of equilibrium of immersed solids, and Hero discussed pneumatic and hydraulic devices and the connection between efflux rate and water head (depth of the mouth). The word "hydraulic" was originally used to describe an Alexandrian invention, the water-powered organ.

The tremendous growth of hydraulic construction during the Roman Empire and the medieval period led to important innovations, such as aqueducts and waterwheels, but added little to the Greeks' understanding of fluid equilibrium and motion. A Renaissance man, Leonardo da Vinci, brought late-medieval mechanics and the emerging experimental trend to bear on these questions. His insights into the pressure-head relation, eddy formation, flux conservation, and open-channel dynamics probably aided Galileo's disciple Evangelista Torricelli, who in 1644 established the proportionality between the efflux velocity and the square root of the water head. Torricelli also explained the principle of the Florentine barometric tube by the balance between the weight of supported mercury and atmospheric pressure.

In seventeenth-century France, Blaise Pascal formulated the law of isotropic pressure, and persuaded his brother-in-law to verify the altitude-dependence of barometric pressure, which in Pascal's view excluded the Aristotelian *horror vacui*. Hydrostatics thus reached maturity. Fluid motion still challenged the new mechanical philosophy. In his *Principia mathematica* of 1687, Isaac Newton discussed fluid resistance in order to show, contra Aristotle and René Descartes, that matter could not fill interplanetary space. By theory and experiment, he established that the resistance of a fluid to motion through it was proportional to the cross section of the moving object, to the fluid density, and to the squared velocity.

Newton's reasoning used the balance between the momentum lost by the object and that acquired by the fluid and a drastic simplification of the flow pattern. In contrast, the Swiss geometer Daniel Bernoulli based his *Hydrodynamica* of 1738 on Leibnizian *vis viva* (kinetic energy) conservation, thus obtaining the relation between wall pressure, velocity, and height (Bernoulli's law). His word "hydrodynamica" expressed the synthesis between conceptions of hydrostatics and hydraulics. Only after suitable extensions of Newtonian dynamics and differential calculus did "hydrodynamics" come to mean a general theory of fluid motion. In 1744 and 1752, Jean Le Rond d'Alembert published two treatises in which he applied his general principle of dynamics to fluid motion and established the paradoxical lack of resistance to the motion of a solid through a perfect fluid. Probably motivated by this breakthrough, in 1755 the Swiss geometer Leonhard Euler obtained the partial-differential equation for the motion of a perfect fluid by equating the forces acting on a fluid element to the product of its acceleration and mass. He also showed how to derive Bernoulli's law from this equation. In his *Méchanique analitique* of 1788, Joseph Louis Lagrange solved Euler's equation for simple cases of two-dimensional fluid motion and proved a few important theorems.

D'Alembert's paradox and the nonlinear structure of Euler's equation deterred geometers and engineers from applying the new fluid mechanics to concrete problems. The French masters of late eighteenth-century hydraulics, Jean-Charles Borda, Charles Bossut, and Pierre-Louis-Georges Du Buat, combined experiment, global balance of momentum or *vis viva,* and physical intuition. Borda and Du Buat corrected Newton's misconceptions about fluid resistance; Borda completed Bernoulli's ideas on efflux and on head loss in a suddenly expanding pipe; Bossut and Du Buat established the proportionality between the loss of head in a long pipe or channel and the squared velocity; Du Buat formulated the general condition of permanent (constant velocity) flow as the balance between wall friction, pressure gradient, and weight.

The scope and accuracy of this semi-empirical approach grew considerably in the nineteenth century with the work of French, British, and German engineers. In the 1830s, the increased interest in canal building and river navigability led

Jean-Baptiste Bélanger and Gaspard Gustave de Coriolis to compute the backwater caused by weirs. Between 1850 and 1870, Henri-Philibert-Gaspard Darcy and Henri-Émile Bazin made extensive measurements of flow in pipes and channels. In Britain, John Scott Russell, William Rankine, and William Froude studied how wave formation, streamlining, and a vessel's skin friction affected ship resistance. Most influential were Froude's model-towing experiments and his formulation of the laws that relate small-scale data to true-scale resistance.

Fundamental hydrodynamics also progressed. The mathematical physicists Simeon-Denis Poisson, Augustin-Louis Cauchy, George Biddell Airy, George Gabriel Stokes, William Thomson (Lord Kelvin), Joseph Boussinesq, and John William Strutt (Lord Rayleigh) provided solutions of Euler's equation for ocean waves, ship waves, canal waves, and solitary waves. In 1858, while studying the aerial motion in organ pipes, Hermann Helmholtz discovered that rotational motion in a perfect, incompressible fluid obeyed remarkably simple conservation laws. Ten years later, Thomson exploited the resultant steadiness of annular vortices to represent atoms of matter. Meanwhile, von Helmholtz and Rayleigh argued that the formation of highly unstable vortex sheets (thin layers of uniformly rotating fluid) behind solid obstacles provided a solution to d'Alembert's paradox.

In 1822, the French engineer-mathematician Claude-Louis Navier inserted a viscosity-dependent term in Euler's equation. As Stokes demonstrated in his memoir on pendulums of 1850, the equation correctly described the regular flows observed for small characteristic lengths and velocities (e.g., the diameter of the bulb and its velocity in the pendulum case), but it seemed useless for the irregular flows observed in hydraulic cases. In the 1840s, Navier's disciple Adhémar Barré de Saint-Venant suggested that a variable effective viscosity (viscosity depending on local agitation) could be used to describe the average large-scale motion in pipes and channels. Saint-Venant's protégé Boussinesq successfully implemented this approach in the 1870s.

Whereas the French separately studied the two kinds of flow—laminar and turbulent, in Thomson's parlance—in 1883 the British engineer Osborne Reynolds studied the transition between them. He found it to occur very suddenly (as had been observed by Gotthilf Hagen in 1839) for a given value of the number LUD/η, where L and U are the characteristic length and velocity of the flow, D the fluid's density, and η the fluid's viscosity. By astute experiments and by analogy with the kinetic theory of gases, Reynolds shed light on the implied instability. Thomson and Rayleigh then pioneered the mathematical study of this question.

Despite the practical orientation of some of its theorists, nineteenth-century hydrodynamics failed to meet hydraulic and other engineering needs. It did produce, however, some of the key concepts that permitted the success of applied fluid mechanics in the twentieth century. Helmholtz's theorems on vortex motion and his concept of surfaces of discontinuity (or vortex sheets) served Ludwig Prandtl's and Theodore von Kármán's theories of fluid resistance, Frederick Lanchester's, Martin William Kutta's, and Nikolai Joukowski's theories of the airfoil, and Vilhelm Bjerknes's theory of meteorological fronts. Reynolds's and Boussinesq's theories inspired Geoffrey Taylor's, Johannes Burgers's, Prandtl's, and Kármán's statistical approaches to turbulence.

The newer fluid mechanics bridged fields as diverse as hydraulics, marine architecture, meteorology, and aeronautics. Large laboratories were built to combine model measurements, theoretical analysis, and technical forecast. Prandtl's Göttingen institute set the trend early in the twentieth century; similar institutes were created in other industrializing countries. The United States and the Soviet Union became leaders in theoretical and applied fluid mechanics.

Olivier Darrigol